MEMORANDUM REPORT BRL-MR-3867

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A SYMPTOM OF PAYLOAD-INDUCED FLIGHT INSTABILITY

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CHARLES H. MURPHY

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13. ABSTRACT (Maximum 200 words)

Observations of instability caused by a moving payload--liquid or solid--have shown that large angular motions are always accompanied by a large spin-down moment. A simple general relation is derived between the side moment and the spin moment caused by the steady-state motion of any movable payload.

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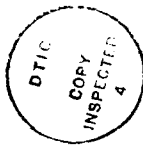| 17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR

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I. Introduction

The angular motion of a projectile in flight can usually be represented as the sum of two coning motions. The stability of a general motion can then be determined by considering the stability of each coning motion separately. For this analysis, an aeroballistic coning axis system with unit vectors $\hat{e}_{xc}$, $\hat{e}_{yc}$ and $\hat{e}_{zc}$ is customary. The $\hat{e}_{xc}$ vector is aligned along the axis of symmetry; the $\hat{e}_{yc}$ vector is in the plane containing the axis of symmetry and the velocity vector and points toward the velocity vector. For constant-amplitude coning motion of amplitude α_c and frequency $\dot{\phi}_c$, the angular velocity of the coordinate system is

$$\vec{\Omega} = \dot{\phi}_c \ (\hat{e}_{xc} \ \cos\alpha_c + \hat{e}_{yc} \ \sin\alpha_c) \tag{1}$$

The aerodynamic moment $\vec{M}_a$ can be expressed in the coning coordinate system as (M_{ax}, M_{ay}, M_{az}). M_{ax} represents the spin moment and is usually described quantitatively by the dimensionless coefficient C_l. M_{az} represents an in-plane moment (a moment causing a motion in the plane of the cone angle); it is related primarily to the static moment coefficient, C_{M_α}, and controls the frequency of the coning motion.[1] Finally, M_{ay} represents a side moment; it is a combination of the damping-in-pitch and Magnus moment coefficients, and controls the growth or decay of the coning motion.

If a projectile has a moving payload — solid or liquid — the moment exerted by this payload can be expressed in coning coordinates as (M_{px}, M_{py}, M_{pz}). The side moment component, M_{py}, can cause spectacular instabilities. When these instabilities occur, a rapid despin is observed; hence a relation between the moving payload's spin moment and its side moment has long been suspected. This correlation between spin and side moment is used as a diagnostic for payload-induced instability.

In this report we will review the experimental observations and theories that deal with this relation for a variety of moving components. We will then derive a very simple relation that applies to all moving payloads in steady-state motion, thus validating the diagnostic tool.

II. Moving Rigid Payload

In 1955 an 8-inch shell, the T317, showed significant range losses and very large spin decays.[2] This shell had several rings held on a central column but free to move within small but nonzero clearances. The actual spin histories of several T317's are given in Reference 2 and are repeated as Figure 1. This figure also gives the spin history for three T347's. The T347 shell has the same external shape, mass, and moments of inertia as the T317 but no movable internal components. In all observed cases, the T317 had a greater spin loss and flew to a lesser range. The relative decrements between the range of each T317 shell and the average range of the T347's are given in the figure. We see that a spin loss of almost 70 Hz was observed for a projectile that flew 11 % short of its proper range.

Several authors [3,4,5] developed steady-state payload motion theories to explain this misbehavior. Reference 5 considered two types of motion: (1) a circular motion of radius ϵ of the payload component center of mass about the projectile's axis of symmetry; (2) a coning motion of angle γ of the spin axis of the payload component about the projectile's axis of symmetry. Both motions were assumed to be at the projectile's coning frequency, $\dot{\phi}_c$, and lagging the projectile coning motion by a phase angle ϕ_a. Under these assumptions, the side moment exerted by the internal component was shown to be

$$M_{py} = A \, \dot{\phi}_c \, \sin \phi_a \tag{2}$$

where:

$$A = \begin{cases} (1) \; m_p \, l_p^2 \, \dot{\phi}_c \; \epsilon \\ \text{or} \\ (2) \; \left(I_{xp} \, p_p - I_{tp} \, \dot{\phi}_c \right) \gamma \end{cases}$$

m_p = mass of payload component

l_p = axial location of payload component relative to projectile center of mass

I_{xp} = axial moment of inertia of payload component

I_{tp} = transverse moment of inertia of payload component

p_p = spin of payload component

More importantly, the roll moment induced by the payload component was shown to be

$$M_{px} = - M_{py} \, \sin \alpha_c \tag{3}$$

III. Liquid Payloads

Liquid payloads have been known to cause very spectacular instabilities. Flight measurements in 1974 of unstable projectiles with spinning liquid payloads showed a most remarkable result.[6] Very large decreases in projectile spin were observed for unstable projectiles performing large-amplitude coning motion.

Figures 2-3 are yawsonde records for a liquid-filled shell fired at a transonic muzzle velocity. The oscillating sun angle, σ_n, indicates a coning motion in excess of thirty degrees after eight seconds of flight. At this time, the slope of Euler spin, $\dot{\phi}$, changes by a factor of ten. Thus projectiles fully filled with liquid show the same spin-down behavior as projectiles with moving rigid payloads. Indeed, this large despin moment occurring for payload-induced instability was suggested by Miller [7] as a design tool, a technique justified by flight tests.[8]

2

The first theoretical relation between side moment and roll moment for liquid payloads was given in Reference 9. This reference assumed that the steady-state motion of a liquid could be approximated by a linearized Navier-Stokes equation and then showed (after considerable algebra) that Equation (3) was valid for a liquid payload. Later, Rosenblat et al.[10] showed that linearization of the Navier-Stokes equation was unnecessary. After three pages of much simpler algebra, Reference 10 showed that *any* liquid in a fully filled payload cavity (provided the liquid satisfies the continuity equation and is in steady-state motion) has the following relationship between its side moment and its roll moment:

$$M_{px} = -M_{py} \tan \alpha_c \tag{4}$$

Note that the linear versions of Equations (3) and (4) are the same but Eq. (4) is the more accurate nonlinear version.

IV. General Moving Payload Moment Relation

The occurrence of Eq. (4) in so many moving payload theories suggests the possibility that some simple general proof of this relation should exist for all possible moving payloads in steady-state motion. Indeed, such a proof was developed in Reference 11 by differentiating the angular momentum of the moving payload.

If $\vec{V}(x, y, z)$ is the velocity vector of the moving payload element located at (x, y, z), the angular momentum of the payload is given by

$$\vec{L} = \iiint \rho \, \vec{R} \times \vec{V} \, dx \, dy \, dz \tag{5}$$

where: $\rho(x, y, z)$ is the payload density and
$\vec{R} = (x, y, z)$ is the position vector of a payload element.

The moment exerted by the moving payload is the negative of the derivative of the payload's angular momentum:

$$
\begin{aligned}
\vec{M}_p &= -\dot{\vec{L}} \\
&= -\left(\dot{L}_1 \, \hat{e}_{xc} + \dot{L}_2 \, \hat{e}_{yc} + \dot{L}_3 \, \hat{e}_{zc} + \vec{\Omega} \times \vec{L} \right)
\end{aligned} \tag{6}
$$

where: (L_1, L_2, L_3) are the components of the payload angular momentum vector in the coning system.

For steady-state coning motion, $\dot{L}_j = 0$ and hence

$$\vec{M}_p = \dot{\phi}_c \ [- L_3 \sin \alpha_c \ \hat{e}_{xc} \ + \ L_3 \cos \alpha_c \ \hat{e}_{yc} \ + \ (L_1 \sin \alpha_c \ - \ L_2 \cos \alpha_c) \ \hat{e}_{zc} \ ] \qquad (7)$$

so that

$$\begin{aligned}
M_{px} &= - \dot{\phi}_c \ L_3 \sin \alpha_c \\
&= - M_{py} \ \tan \alpha_c \qquad (8)
\end{aligned}$$

Thus the presence of a payload-induced side moment can always be determined by the roll moment for large coning motion.
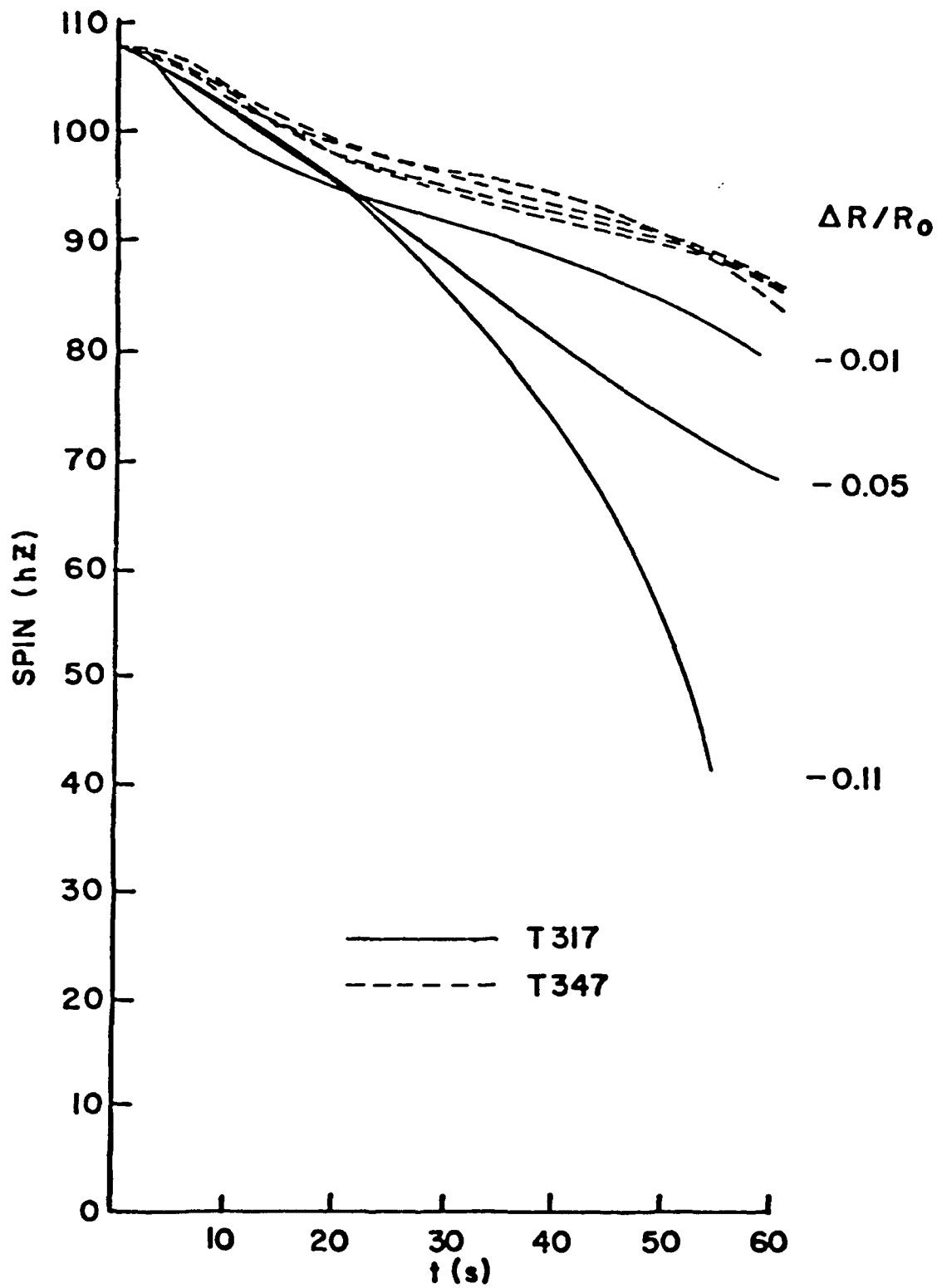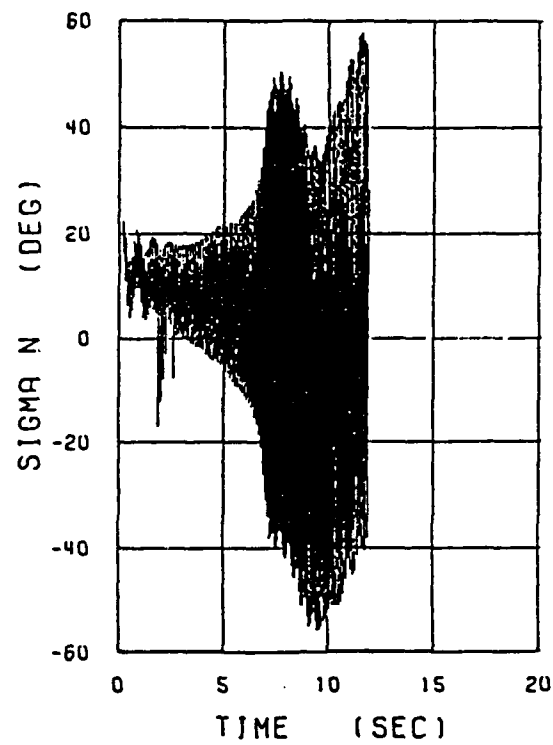
Figure 1. Measured spin histories of T317.

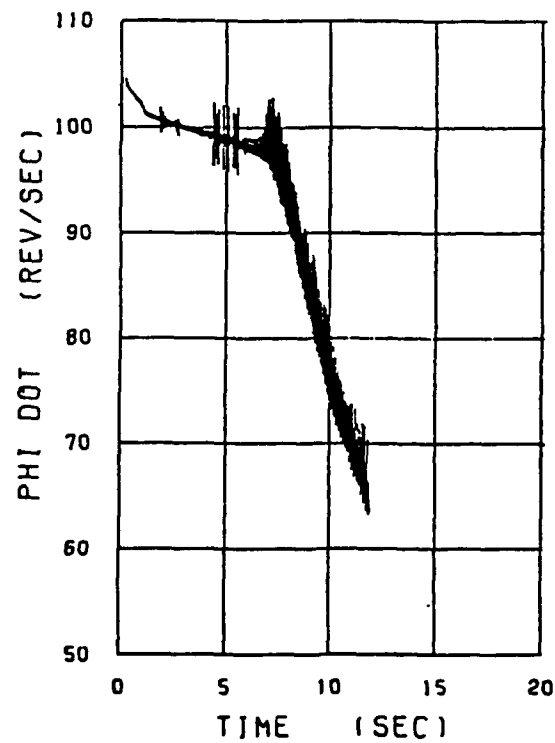**Figure 2.** Sun angle history of unstable liquid-filled shell.

Figure 3. Spin history of unstable liquid-filled shell.

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